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Ecological restoration and rewilding: two approaches with complementary goals?

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ABSTRACT

As we enter the UN Decade on Ecosystem Restoration (2021–2030) and address the urgent need to protect and restore ecosystems and their ecological functions at large scales, rewilding has been brought into the limelight. Interest in this discipline is thus increasing, with a large number of conceptual scientific papers published in recent years. Increasing enthusiasm has led to discussions and debates in the scientific community about the differences between ecological restoration and rewilding. The main goal of this review is to compare and clarify the position of each field. Our results show that despite some differences (e.g. top-down *versus* bottom-up and functional *versus* taxonomic approaches) and notably with distinct goals – recovery of a defined historically determined target ecosystem *versus* recovery of natural processes with often no target endpoint – ecological restoration and rewilding have a common scope: the recovery of ecosystems following anthropogenic degradation. The goals of ecological restoration and rewilding have expanded with the progress of each field. However, it is unclear whether there is a paradigm shift with ecological restoration moving towards rewilding or *vice versa*. We underline the complementarity in time and in space of ecological restoration and rewilding. To conclude, we argue that reconciliation of these two fields of nature conservation to ensure complementarity could create a synergy to achieve their common scope.

Key words: conservation biology, ecosystem function, ecosystem engineer, paradigm, restorative activities.

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I. INTRODUCTION

To counteract biodiversity and ecosystem service collapse (IUCN, 2021; Cowie, Bouchet & Fontaine, 2022), simply protecting existing ecosystems and species of high conservation value is insufficient, and restoring degraded ecosystems is necessary (Young, 2000). This argument is largely acknowledged in international agreements and initiatives, such as IUCN resolutions (IUCN, 2012), the Convention on Biological Diversity (CBD, 2010), the Bonn Challenge launched in 2011 with the aim of restoring 350 million hectares of degraded forest and agricultural landscape by 2030 (Verdone & Seidl, 2017), and the United Nations Environment Programme (IRP, 2019). The UN Decade on Ecosystem Restoration (2021–2030) has the declared aim of preventing, stopping, and reversing ecosystem degradation worldwide (UN, 2019).

To restore ecosystems and their taxonomic (i.e. species composition of an ecosystem) or functional (i.e. ecological functions such as water flux or nutrient cycles) characteristics (see Table 1 for a glossary of terms), various disciplines have emerged, each with particular paradigms. Among these disciplines, we focus herein on ecological restoration and rewilding. The concept of ecological restoration began in the mid 1930s and can be defined as '*the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed*' [Gann *et al.* (2019, p. S7) based on SER (2004)]. Rewilding emerged later at the end of the 1990s and one of the latest definitions is the process of rebuilding a natural ecosystem after human disturbance, by restoring processes and food webs, to become a self-sustaining and resilient ecosystem (Carver *et al.*, 2021). It is also a potentially cost-effective solution that has increased in popularity during the last decade both in the scientific community and in the wider media (Pettorelli, Durant & du Toit, 2019). The legitimacy of rewilding as a different approach from ecological restoration (Corlett, 2016; Derham, 2019; du Toit & Pettorelli, 2019; Pettorelli *et al.*, 2019) has been strongly debated, likely because restoration and rewilding share a common scope, i.e. the recovery of ecosystems following anthropogenic disturbance and/or damage. In particular, opponents have argued that rewilding belongs in the restoration continuum and does not represent a novel approach (Nogués-Bravo *et al.*, 2016; Hayward *et al.*, 2019*b*,*c*). On the other hand, rewilding proponents have underlined differences in terms of goals. Rewilding is open-ended and encourages self-determined natural processes and functional targets – with the possibility of using taxonomic substitutions. Its top-down approaches (such as trophic rewilding) represent a marked difference from the bottom-up approaches used in ecological restoration (Derham, 2019; Anderson *et al.*, 2019; du Toit & Pettorelli, 2019). In this review we retrace the histories of restoration ecology and rewilding. We compare and clarify the position of each field using the existing literature and previous analyses (Corlett, 2016; Miller & Hobbs, 2019; du Toit & Pettorelli, 2019) and include the most recent research and examples of their implementation in practice. Because paradigms and their use evolve constantly, we provide a framework for reconciliation of these two paradigms in the future through complementarity.

II. METHODS

This review is based on English-language scientific papers found in *Web of Science* using search term '*wilding' AND 'ecological restoration' OR 'restoration ecology' with no date or geographical limits. We aimed for a representative review of research and discussion on these topics, but not a systematic analysis. The search returned 80 articles. By reading the title, abstract and key words we selected the 68 articles that dealt more specifically with both approaches (not just dealt with one and mentioned the other). We then read these 68 papers in full. We also searched *Web of Science* using the same component terms individually. For '*wilding', 1,044 results were returned. We then selected only publications that were listed in the following categories: Ecology, Biodiversity Conservation, Environmental Sciences, and Environmental Studies ($N = 530$). A very high number of articles were returned for 'ecological restoration' even after refining by the categories Ecology, Environmental Sciences, Biodiversity Conservation, Environmental Studies, Plant Sciences, and Forestry ($N = 7{,}834$). From these we first selected reviews and conceptual papers, which specifically related to scopes, aims and histories of the strategies, and expanded the selection to original articles to add examples. We also searched the references of the studies that passed our initial screening. The final total was 215 scientific articles which were read in full.

III. TWO PARADIGMS

(1) Emergence of the two paradigms and their principles

Agreements and disagreements about the benefits and limitations of the two disciplines permit one to refine their

Table 1. Glossary.

	Definition
Assisted colonisation	A form of conservation introduction (see conservation translocation) defined as the intentional movement, by humans, of an organism outside its indigenous range to avoid extinction of populations due to current or future threats (IUCN/SSC, 2013).
Conservation translocation	The intentional movement, by humans, of organisms to save populations from extinction (Seddon *et al.*, 2014); movement of species, sub-species or lower taxa in a form that can survive and reproduce. Reinforcements and reintroductions are two types of translocations used for population restoration in the indigenous range of species. Conservation introductions (assisted colonisation and ecological replacement) are translocations outside the indigenous range (Seddon *et al.*, 2014).
Ecological functions	The flow of energy and materials through an ecosystem or landscape (Manning *et al.*, 2018) that sustain an ecological system. Can include a role (e.g. primary producer) and the bearer of the function (e.g. a plant) (Jax, 2005).
Ecological replacement/ taxon replacement	A form of conservation translocation which facilitates the recovery of an ecological function lost through extinction, by introducing an appropriate substitute for the lost species (IUCN/SSC, 2013).
Ecological restoration	"*the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed*" (Gann *et al.*, 2019, p. S7)
Ecosystem services	The benefits society obtains from ecosystems, for example provisioning services, regulating services, cultural services, or supporting services (Millennium Ecosystem Assessment (Program), 2005).
Goals (in the context of restoration)	"*formal statements of the medium to long-term desired ecological or social condition, including the level of recovery sought*" (Gann *et al.*, 2019, p. S15).
Hybrid and novel ecosystem	"*A novel ecosystem is a system of abiotic, biotic and social components that, by virtue of human influence, differ from those that prevailed historically, having a tendency to self-organize and manifest novel qualities without intensive human management*" (Hobbs *et al.*, 2013, p. 58). If the ecosystem is altered but remains near to its historic state, it can be considered as a hybrid state (Hobbs *et al.*, 2009).
Keystone species	Species whose disappearance leads to cascading effects in an ecosystem, and precipitates other species losses. There are different types of keystone species (e.g. predators, prey, plants), underlining the complexity of the interactions that comprise an ecosystem (Mills *et al.*, 1993).
Naturalness	The quality of being natural, in opposition to artificiality (Chapman, 2004).
Reclamation	"*The process of making severely degraded land (e.g. former mine sites or wastelands) fit for cultivation or a state suitable for some human use*" (Gann *et al.*, 2019, p. S37).
Rehabilitation	"*Management actions that aim to reinstate a level of ecosystem functioning on degraded sites, where the goal is renewed and ongoing provision of ecosystem services rather than the biodiversity and integrity of a designated native reference ecosystem*" (Gann *et al.*, 2019, p. S37).
Reinforcement	One type of conservation translocation. It involves the release of an organism into an existing population of conspecifics to enhance population viability (Seddon *et al.*, 2014).
Reintroduction	One type of conservation translocation, with the aim to re-establish a population in an area after local extinction (Seddon *et al.*, 2014). The intentional movement and release of an organism by humans inside a species' indigenous range from which it has disappeared (IUCN/SSC, 2013).
Scope (in the context of restoration or rewilding)	Is the "*thematic focus of a project*" (Gann *et al.*, 2019, p. S15).
Rewilding	The process of rebuilding a natural ecosystem after human disturbance, by restoring processes and food webs, to become a self-sustaining and resilient ecosystem (Carver *et al.*, 2021)
Umbrella species	The conservation strategy promoting the idea that the protection of one species will benefit co-occurring species (Branton & Richardson, 2011).
Wilderness	An area unaffected by modern human activities with its natural life community (Jørgensen, 2015).

definitions and associated principles. The most recent definition of ecological restoration is from Gann *et al.* (2019, p. S7): '*the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. (…) Ecological restoration aims to move a degraded ecosystem to a trajectory of recovery that allows adaptation to local and global changes, as well as persistence and evolution of its component species. (…) Ecological restoration projects or programs include one or more targets that identify the native ecosystem to be restored (called reference model), and project goals that establish the level of recovery sought. (…) An ecological restoration project or program should aspire to substantial recovery of the native biota and ecosystem functions.*' Gann *et al.* (2019) also provide eight principles that underpin ecological restoration (Table 2).

A general definition of rewilding is provided by Carver *et al.* (2021, p. S7): '*Rewilding is the process of rebuilding, following major human disturbance, a natural ecosystem by restoring natural processes and the complete or near complete food web at all trophic levels as a self-sustaining and resilient ecosystem with biota that would have been present had the disturbance not occurred.*' Carver *et al.* (2021) also provide 10 principles underpinning rewilding (Table 2).

Among the principles associated with the definitions of the two approaches, some appear to be very similar (Table 2). Both paradigms aim for the recovery of ecological processes. Practices should be based on comprehensive knowledge from different sources and engage multiple appropriate stakeholders. Both aim to consider the effects of climate change.

Both disciplines consider intervention scales as important: rewilding employs landscape-scale planning, while ecological restoration projects are believed to gain value when applied at large scales. The two paradigms are also informed by reference ecosystems, but ecological restoration is informed by native (if possible historical) ecosystems whereas rewilding is informed by natural and functional ecosystems – even if they differ from past ecosystems. Other principles are unique

Table 2. Principles of ecological restoration from Gann *et al.* (2019) and rewilding from Carver *et al.* (2021) and examples of their application. The rewilding principles listed by Carver *et al.* (2021) are re-ordered to align with the principles of ecological restoration to which they are most similar. A coloured font is used to emphasise similarities between the two disciplines, whereas a black font indicates features particular to each discipline).

Ecological restoration		Rewilding	
Principles	Examples of application	Principles	Examples of application
1. Engages stakeholders	Active community participation, supporting local livelihoods, respecting people's values and perspectives [see Fox & Cundill (2018) for further examples].	6. Rewilding requires local engagement and support.	Gain of local support by emphasising the social, cultural and economic potential of the Iberá wetlands rewilding project (Pettersson & de Carvalho, 2021).
2. Draws on many types of knowledge	Using indigenous methods to avoid plant invasion during tropical forest restoration project (Douterlungne *et al.*, 2010). Use of local historic knowledge about fish population levels (Eckert *et al.*, 2018).	7. Rewilding is informed by science, traditional ecological knowledge (TEK), and other local knowledge.	Rewilding Lapland project is closely linked to the Sámi people and their local ecological knowledge is increasingly necessary to understand the ecosystem but has not yet been taken into account (Rouet-Leduc & von Essen, 2019).
3. Is Informed by native reference ecosystems, while considering environmental change	Seagrass restoration informed and compared with historical levels (Orth *et al.*, 2020). Models of ecological niche under climate change used to select appropriate vegetation in Mexico (Gelviz-Gelvez *et al.*, 2015).	5. Rewilding should anticipate the effects of climate change and where possible act as a tool to mitigate impacts.	Strategies permitting rewilding even in the context of drought due to climate change (Falcón & Hansen, 2018). Mitigation due to herbivore activities in the Pleistocene Park in Siberia, Russia (Zimov, 2005; Fischer *et al.*, 2022).
4. Supports ecosystem recovery processes	Indirectly by the recovery of the ecosystem species composition (among numerous examples, see Slodowicz *et al.*, 2023).	3. Rewilding focuses on the recovery of ecological processes, interactions, and conditions based on reference ecosystems.	Reintroduction of elephant (*Loxodonta cyclotis*) in South African savannah leading to a more open landscape (Gordon *et al.*, 2022); beaver (*Castor fiber*) reintroduction in Scotland and effect of the ponds created by their dams (Law *et al.*, 2017). Wildfire and free-roaming bison (*Bison bison*) shaping landscape heterogeneity (Fuhlendorf *et al.*, 2009).
5. Is assessed against clear goals and objectives, using measurable indicators	Framework for setting clear justified goals and selecting indicators (Prach *et al.*, 2019). Several reviews of indicators (Pander & Geist, 2013; Suganuma & Durigan, 2015; Gatica-Saavedra *et al.*, 2017).		
6. Seeks the highest level of recovery attainable.	Restoration of a steppe after a pipeline leak, with the undamaged native ecosystem as the highest level of recovery (Bulot *et al.*, 2014).		
7. Gains cumulative value when applied at large scales.	Extension of permanent water due to large-scale vegetation restoration in China (Zeng *et al.*, 2020).	2. Rewilding employs landscape-scale planning that considers core areas, connectivity, and co-existence.	Study of connectivity for recolonisation of Europe's larger herbivores (Bluhm *et al.*, 2023).

(Continues on next page)

Table 2. *(Cont.)*

Ecological restoration		Rewilding	
Principles	Examples of application	Principles	Examples of application
8. Is part of a continuum of restorative activities.	Different approaches used to restore the same steppe area: soil transfer (Bulot *et al.*, 2014), rehabilitation using sowing of nurse species (Jaunatre *et al.*, 2014), rehabilitation with topsoil transfer with water table contact (Chenot *et al.*, 2017).		
		1. Rewilding utilises wildlife to restore trophic interactions.	Reintroduction of pampas deer (*Ozotoceros bezoarticus*), collared peccary (*Pecari tajacu*), tapir (*Tapirus terrestris*) (Zamboni *et al.*, 2017; Torres *et al.*, 2018).
		4. Rewilding recognises that ecosystems are dynamic and constantly changing.	Forest regeneration in Mediterranean mountains under passive human management (Pereira & Navarro, 2015).
		8. Rewilding is adaptive and dependent on monitoring and feedback (also for ecological restoration, see part III. (4)).	Rewilding Europe reports, such as for the reintroduction of the bison in Carpathia (Vlasakker, 2014) (https://rewildingeurope.com/publications/).
		9. Rewilding recognises the intrinsic value of all species and ecosystems.	By focusing on different ecosystems and species, e.g. on islands (Hansen *et al.*, 2008), at different latitudes (Zimov, 2005; Vlasakker, 2014; Pettersson & de Carvalho, 2021), or on carnivores or herbivores (Ripple & Beschta, 2012; Fuhlendorf *et al.*, 2009; Law *et al.*, 2017; Zamboni *et al.*, 2017; Torres *et al.*, 2018; Gordon *et al.*, 2022).
		10. Rewilding requires a paradigm shift in the coexistence of humans and nature.	Attitudes towards rewilding can vary strongly within a community (Bauer *et al.*, 2009; López-i-Gelats *et al.*, 2021).

to only one discipline, such as the idea that ecological restoration is part of a continuum of restorative activities (Principle 8 of ecological restoration) or that rewilding uses wildlife to restore trophic interactions (Principle 1 of rewilding).

Definitions of ecological restoration and rewilding have evolved over time. Indigenous people and land managers have been practicing restorative land management for thousands of years (Jordan & George, 2011), and some restoration-like projects were implemented at large scales as early as the mid-19th century, such as reforestation of Tijuca National Park, Rio de Janeiro, Brazil (Drummond, 1996; Freitas, Neves & Chernicharo, 2006) or reforestation in the French Alps (Buisson *et al.*, 2018) with both native and exotic tree species. Ecological restoration as a scientific discipline emerged in the mid-1930s in the USA with the work of Leopold (1949). One of the first and longest documented restoration projects was an attempt to restore North American tallgrass prairies – Curtis Prairie (Curtis, 1955; Cottam & Wilson, 1966) and Greene Prairie (Allison, 2002) – in Wisconsin, on land ploughed and cultivated previously for agricultural use. The paradigm was novel because it was more ecocentric than the restorative land management previously practised (Jordan & George, 2011), and aimed to restore the whole ecosystem rather than sites for human purposes (rehabilitation).

By the 1980s, early definitions of ecological restoration promoting the use of ecological knowledge to restore degraded ecosystems were provided by Bradshaw & Chadwick (1980) and by Berger in *Restoring the Earth* (cited in Martin, 2017). Ecological restoration increasingly included a variety of ecosystems, such as woodlands, wetlands or streams. The Society for Ecological Restoration (SER) was founded in 1987 and has published the journal *Restoration Ecology* since 1993 (Harden, Fox & Fox, 2004). Since then, the scientific literature on the topic has increased, and the definition of ecological restoration has evolved.

When the SER was created, the Society defined ecological restoration as: '*the intentional alteration of a site to establish a defined indigenous, historic ecosystem. The goal of this process is to emulate the structure, functioning, diversity, and dynamics of the specified ecosystem*' (cited in Aronson *et al.*, 1993, p. 8–9). Subsequent debate centred on two types of restoration: *sensu stricto* and *sensu lato*. Restoration *sensu stricto* '*seeks to re-establish a full inventory of pre-existing species*' (Aronson *et al.*, 1993, p. 14). Restoration *sensu lato* simply aimed to halt degradation and put the damaged ecosystem on a trajectory that approached that present prior to the disturbance or the transformation to an alternative state. The SER refined the *sensu lato* definition to '*the process of assisting the recovery of damaged, degraded or destroyed ecosystems*' (SER, 2004, p. 2). Thus, restoration *sensu lato* also included activities such as reclamation and rehabilitation (SER, 2004). In 2016, the United Nations Convention on Biological Diversity (CBD, 2016, p. 4) added the goal to attain '*[…] sustaining ecosystem resilience and conserving biodiversity*'. Reflections about the practical limits of the paradigm – and the need to refine definitions – have since been regularly published. For example, the SER definition was amended to include benefits to humans, such as ecosystem goods and services (Martin, 2017), and the terms '*sensu stricto*' and '*sensu lato*' were abandoned. Ecological restoration (formerly restoration *sensu stricto*) was re-defined as a restorative activity at one end of a restorative continuum (formerly ecological restoration *sensu lato*) where ecological health and biodiversity outcomes, as well as the quality and quantity of ecosystem services are the highest (Gann *et al.*, 2019).

The discipline of rewilding has been generating increasing interest in recent years (Pettorelli *et al.*, 2019). The overall paradigm of rewilding fits with ecocentric ecological restoration, but was innovative because it is based on the idea of allowing nature to restore itself, a spontaneous recovery process sometimes aided by the reintroduction of keystone and umbrella species. Definitions of rewilding also evolved over time and this process has been described in several articles (Jørgensen, 2015; Prior & Ward, 2016; Cloyd, 2016; Gammon, 2018). There have been multiple definitions, reflecting the multitude of rewilding approaches, but all have the same underlying idea: facilitating the recovery of ecosystems by promoting natural processes, and by allowing space for wildlife along with no or minimal human management. Rewilding first appeared in the literature in North America with the concept of the 'three Cs': Core, Corridor, Carnivore (Soule & Noss, 1998). This concept highlighted the importance of core zones, for nature protection, the connections made by corridors between them, and the reintroduction of top predators as keystone species. In the early 2000s, two rewilding approaches were defined. Pleistocene rewilding (mostly in North America) promoted the return of extant megafauna (herbivores and predators) to replace species that had disappeared largely because of hunting in the late Pleistocene (13,000 years ago) (Donlan, 2005; Donlan *et al.*, 2006). It aimed at recovering lost trophic functions by reintroducing locally extinct species, or taxon replacement (Seddon *et al.*, 2014; Svenning, Munk & Schweiger, 2019).

Taxon replacement, also called ecological replacement (Seddon *et al.*, 2014), aims at recovering lost ecological functions by introducing functionally similar non-native species. The constraints imposed by Pleistocene rewilding, such as the historical reference and the need for large areas, ethical issues, social acceptance, and costs (Rubenstein *et al.*, 2006; Toledo, Agudelo & Bentley, 2011; Rubenstein & Rubenstein, 2016; du Toit, 2019), led to reconsideration of the concept, such as selecting only species extirpated less than 5,000 years ago and it was renamed 'trophic rewilding' (Svenning *et al.*, 2016). The definition of trophic rewilding is an '*ecological restoration strategy that uses species introductions to restore top-down trophic interactions and associated trophic cascades to promote self-regulation of biodiverse ecosystems*' (Svenning *et al.*, 2016, p. 898). The potential of keystone species for restoring ecological functions, such as 'megatrees' that affect water fluxes, carbon distribution, and habitat provision, has also been studied (Schweiger & Svenning, 2020). The use of taxon replacement developed for Pleistocene rewilding was reformulated for an island context, including taxon replacement of both animals and plants (Burney & Burney, 2007; Hansen, Kaiser & Mueller, 2008; Hansen, 2010; Wood *et al.*, 2013). For example, on Ile aux Aigrettes in Mauritius, the disappearance of the native giant tortoise led to a reduction in seed dispersal of the large-fruited endemic ebony (*Diospyros egrettarum* I. Richardson), which recovered following introduction of the closely related Aldabra giant tortoise *Aldabrachelys gigantea* (Schweigger) (Griffiths *et al.*, 2011). The recovery of large areas of wild land, for example at a country scale in Scotland (Brown, Mcmorran & Price, 2011; Jørgensen, 2015) through reintroduction has been implemented in Europe and the Middle East (Price, 2011; Brown *et al.*, 2011), in particular by the reintroduction of locally extinct herbivores without a defined time reference, in contrast to Pleistocene rewilding. However, in these reintroductions there is consciousness of the fact that the longer ago the extinction was, the more difficult it is to achieve social acceptance (Jørgensen, 2015). Subsequently in Europe, the increasing abandonment of agricultural land and the will to allow landscape recovery has led to the emergence of passive rewilding – sometimes called ecological rewilding (Ceauşu *et al.*, 2015; Corlett, 2016) – referring to the spontaneous return of nature following the cessation of human activities (Höchtl, Lehringer & Konold, 2005; Navarro & Pereira, 2015; García-Barón *et al.*, 2018; Carver, 2019; García-Ruiz *et al.*, 2020). The term rewilding has also been used with reference to the release of captive-bred animals into the wild (Jamieson, 2008; Ji *et al.*, 2013; Zheng *et al.*, 2013), which is traditionally known as conservation translocation (reinforcement and reintroduction).

To address the pressing issue of climate change effects, extinctions and ecosystem degradation, the 3Cs model (Carroll & Noss, 2021), trophic rewilding (Cromsigt *et al.*, 2018; Jarvie & Svenning, 2018; Sandom *et al.*, 2020), and island taxon replacement (Falcón & Hansen, 2018) have received renewed interest. Scientists are discussing the mitigation potential of rewilding as it provides large protected areas containing longitudinal and altitudinal gradients and microrefugia (Carroll & Noss, 2021), and involves megafauna which could help to mitigate negative impacts of climate change by altering, for example, the fire regime, carbon sequestration and nutrient transport (Bakker & Svenning, 2018; Cromsigt *et al.*, 2018; Sandom *et al.*, 2020). Scientists increasingly suggest mitigation strategies to aid rewilding in a changing world (e.g. provision of shelters and water holes for giant tortoises to mitigate climate heating impacts; Falcón & Hansen, 2018).

Naturalness and wilderness (see Table 1) have been discussed in the context of both ecological restoration (Chapman, 2006; Prober *et al.*, 2019) and rewilding (Prior & Brady, 2017; Derham, 2019). It has been argued that outcomes of ecological restoration and rewilding projects can be placed on a gradient of naturalness/wilderness defined by the intensity of degradation and human intervention (management), with less naturalness when the damage is major and human management is significant and continued (Van Meerbeek *et al.*, 2019; Carver *et al.*, 2021).

As we can see in the literature, ecological restoration and rewilding have different origins and have emerged from different concepts. The similar scope they share – the recovery of ecosystems after human damage – has also led to converging discussions concerning naturalness and human engagement.

(2) Reference ecosystems, historical legacies and predictability

According to the current definitions and associated principles (Gann *et al.*, 2019; Carver *et al.*, 2021), the two disciplines and their paradigms refer to processes linked with the restoration of ecosystems – and functions – that have been degraded. The objective is to drive ecosystems along a trajectory of recovery. Moreover, the two paradigms through their associated principles, and to some extent in the literature, take climate change into account (Harris *et al.*, 2006; Corlett, 2016; Prober *et al.*, 2019; Wilsey, 2021). Scientists argue that rewilding (Cromsigt *et al.*, 2018; Olofsson & Post, 2018; Schweiger & Svenning, 2020; Lehmann, 2021) and ecological restoration (Bustamante *et al.*, 2019; Littleton *et al.*, 2021) can both be mitigation tools (but this is debated in the framework of ecological restoration, for further details see Bullock *et al.*, 2022). However, the two strategies have distinct goals, and therefore different approaches.

Ecological restoration is generally (see Section IV.1.*a*) based on historical benchmarks, using native undamaged ecosystems as a reference or target. A point still debated among scientists in ecological restoration is the changing role of history and the possible acceptance of an open-ended vision, with the use of hybrid and novel ecosystem concepts (Perring, Standish & Hobbs, 2013; Murcia *et al.*, 2014; Higgs *et al.*, 2014; Miller & Hobbs, 2019). The notions of *hybrid ecosystem* and *novel ecosystem* were introduced by Hobbs *et al.* (2006) and Hobbs, Higgs & Harris (2009) to illustrate that the dynamics of ecosystem development can sometimes lead to an ecosystem that differs from the historical precursor, i.e. to a new ecosystem, or to a hybrid between the novel and the historical ecosystems. The concepts of *hybrid* and *novel ecosystems* have been highlighted by cases of extensive ecological modifications, such as in post-industrial areas (Conradi, Henriksen & Svenning, 2021).

Rewilding is generally described as having no precisely defined endpoint other than the recovery of ecological function (Perino *et al.*, 2019; du Toit & Pettorelli, 2019; Klop-Toker *et al.*, 2020). This is notably linked to the lower predictability associated with wildlife reintroduction or introduction, of the *laissez-faire* (hands-off) approach, and the aim to restore ecological functions rather than the historical species composition.

Predictability is also discussed in ecological restoration: as restoration generally has specific targets, unforeseen outcomes due to environmental constraints and variation are a risk in all projects but are often not well understood (Brudvig *et al.*, 2017; Brudvig & Catano, 2021).

The role of history remains important in ecological restoration. While the historical ecosystem is not a target to reach, historical knowledge is used as a basis for setting goals informed by the past (Case & Hallett, 2021). The target or reference model '*indicates the expected condition that the restoration site would have been in had it not been degraded. This condition is not the historic condition, but rather reflects background and predicted changes in environmental conditions*' (Gann *et al.*, 2019, p. S37). In rewilding, the historical ecosystem is not a target to reach either, even if it helps provide a vision of 'pristine' or 'prehistoric' ecosystems. Historical knowledge and ecological memory are used to inform natural processes for the re-establishment of functioning ecosystems (Schweiger *et al.*, 2019).

(3) Key ecological concepts, methods and scale

(*a*) *Scale-dependent ecological succession*

Currently, the two paradigms both recognise the importance of actions at large scales for the recovery of ecosystems and their adaptation to climate change. Nevertheless, ecological restoration projects have traditionally been implemented mostly at small scales (e.g. 67% of restoration projects in Colombia are implemented over areas less than 100 ha, with a mean of 29 ha; Murcia *et al.*, 2016), limited by the intensity and complexity of interventions, the long-term nature of restoration trajectories, funding challenges, and constraints on identifying targets (Manning, Lindenmayer & Fischer, 2006). More recently, major investments have allowed the support of larger-scale restoration projects [e.g. the Forest Restoration in Landscapes project with aims such as the restoration of 1,550–1,800 km^2 of native Caledonian Forest (Mansourian, Vallauri & Dudley, 2005) or the Atlantic Forest Restoration Pact in Brazil aiming to restore 5 million hectares by the year 2050 (Brancalion *et al.*, 2013)]. Rewilding, on the other hand, has focussed on large-scale activities since its origins, i.e. to create regional networks of natural areas which can support large predators

(Soule & Noss, 1998). In practice, rewilding projects are implemented at scales ranging from several hundreds of hectares [850 ha Côa Valley in Portugal (Gordon *et al.*, 2021*a*); 1400 ha in the Knepp estate, England (Schulte to Bühne *et al.*, 2022)], to bioclimatic scales (e.g. passive forest regeneration in Mediterranean mountains with land abandonment; García-Ruiz *et al.*, 2020), up to several thousands of hectares (17,000 ha in the National Swiss Park; 150,000 ha in Iberá, Argentina; Torres *et al.*, 2018).

(*b*) *Bottom-up and top-down approaches*

Even if the scope of both paradigms is to achieve ecosystem recovery, their approaches and goals are different. Rewilding focuses on recovery of functions of all trophic levels, often – in the case of active rewilding – with a top-down approach where large herbivores and predators (megafauna) drive functions (Hayward *et al.*, 2019a; Miller & Hobbs, 2019; Svenning *et al.*, 2019). On the other hand, ecological restoration projects focus on the recovery of component species – and only indirectly on their ecological functions – working towards metrics of habitat quality (abiotic resources such as soil) and maximising the number of target species, which frequently represent lower trophic levels (producers). Thus restoration could be characterised as a bottom-up approach, often focussing on plants and soils (Young, Petersen & Clary, 2005; Brudvig, 2011; Jones, 2017; Hale *et al.*, 2019; Miller & Hobbs, 2019; Lengyel *et al.*, 2020). Nevertheless, examples of ecological restoration projects with a top-down approach are implemented, e.g. including eradication of invasive species through direct management actions (e.g. shooting, poisoning) (Norton, 2009; Capizzi, 2020). Eradication methods are not developed within the framework of rewilding, and mitigating possible invasions by restoring the lost trophic chain has been discussed with hope and cautions (see Derham *et al.*, 2018).

(*c*) *Assisted dispersal: introduction, reintroduction, translocation methods*

Translocation for conservation is used by both paradigms (IUCN/SSC, 2013). For example in ecological restoration, seed sowing or planting of saplings is widely used to restore degraded habitats (Palma & Laurance, 2015). Concerning rewilding, active reintroductions of wild animals are frequent practices, such as pampas deer *Ozotoceros bezoarticus* Linneaus, collared peccary *Pecari tajacu* Linneaus, tapir *Tapirus terrestris* Linneaus (Zamboni, Di Martino & Jiménez-Pérez, 2017; Torres *et al.*, 2018), and beavers *Castor fiber* Linnaeus (Law *et al.*, 2017). It seems important to note that sometimes old reintroduction projects focusing on species conservation and population re-establishment are now studied under the scope of rewilding, to evaluate the effects of keystone species such as wolves *Canis lupus* Linnaeus in the USA and elephants *Loxodonta cyclotis* Matschie in South Africa (Ripple & Beschta, 2012; Gordon *et al.*, 2022). Taxonomic replacements and de-extinction are often discussed – but de-extinction has not yet been applied in the framework of rewilding or ecological restoration (Corlett, 2016; du Toit & Pettorelli, 2019). Rewilding projects tend to use taxonomic replacements, such as Heck cattle *Bos taurus* Linnaeus and Konik ponies *Equus ferus caballus* Linnaeus as surrogates for aurochs *Bos primigenius* Bojanus and tarpans *Equus ferus gmelini* Boddaert (e.g. projects of Rewilding Europe). As discussed in Section II.1, another example is the introduction of the Aldabra giant tortoise outside its indigenous range to restore the natural function of an extinct tortoise. De-extinction for rewilding has been discussed for both animals (Lorimer & Driessen, 2013; Lovász, Fages & Amrhein, 2021) and plants (Albani Rocchetti *et al.*, 2021). De-extinction uses retro-breeding techniques, with the selection of species that are morphologically similar to the extinct one or with the most similar genome. De-extinction of animals such as the woolly mammoth, using DNA and cloning (Martinelli, Oksanen & Siipi, 2014), is only conjectured at present. The de-extinction of plants would be based on the use of herbarium specimens (germination of old diaspores, plant tissue culturing) (Albani Rocchetti *et al.*, 2021). Introgression breeding, transgenesis, cisgenesis are techniques that could be used in plant rewilding (i.e., reverse breeding), for sustainable agricultural purposes, to reintroduce properties of wild relatives of crops to strengthen them without losing yield (Palmgren *et al.*, 2015; Andersen *et al.*, 2015). The de-extinction of plants could be used in rewilding in the same manner as for animals, to reintroduce lost ecosystem engineers.

(4) Human engagement and human management continuum

The two paradigms both promote the engagement of stakeholders and the use of knowledge from a wide range of sources (e.g. scientific publications, indigenous knowledge) (Gann *et al.*, 2019; Carver *et al.*, 2021). Both underline the need for monitoring projects and feedback to consolidate the results, ameliorate negative impacts, or to re-orientate the actions – a method called adaptive management (Carver *et al.*, 2021). Ecological restoration and rewilding projects include stakeholders during their design to allow better integration into socio-economic processes and structures. However, it is likely that engagement from stakeholders is more easily facilitated and made more concrete in ecological restoration than in rewilding because the former involves management plans while the latter involves *laissez-faire* approaches (Furness, 2021). Land abandonment and forest regeneration in marginal areas are *laissez-faire* approaches which do not necessarily require the engagement of stakeholders or adaptive management (Navarro & Pereira, 2015).

The coexistence of humans and nature, and public perception play important roles in both paradigms. In ecological restoration, public perception can be beneficial or detrimental to a project, and this perception can vary strongly with the socio-cultural environment (Piégay *et al.*, 2005). Although initially rewilding was perceived and criticised as excluding humans from rewilded zones (Jørgensen, 2015), more recently the inclusion and support of stakeholders has been argued to be critical (Perino *et al.*, 2019). This can limit conflicts between people and apex predators such as wolves and bears, or with large herbivores which can be seen as resource competitors by herders. Moreover, this coexistence can reconnect people with nature (Perino *et al.*, 2019). The inclusion of people in rewilding projects could be facilitated by opinion polls helping managers to understand the fears and expectations of the public and by presenting strong arguments about social, cultural and economic potential (Pettersson & de Carvalho, 2021). Moreover, participative approaches can be used, including in project design (with methods, such as focus groups) and by taking part in monitoring and management. Such involvement can facilitate communication, awareness and the feeling of ownership but can also lead to the interruption of a project if people do not support it.

People are not necessarily excluded during either ecological restoration or rewilding projects. Indeed, some projects involve areas where humans have abandoned the land for economic reasons, such as reclaimed mine sites or quarries (Cooke & Johnson, 2002), agricultural land abandonment (Jaunatre, Buisson & Dutoit, 2014; Navarro & Pereira, 2015; Carver, 2019), or following large-scale industrial catastrophes such as in Chernobyl or Fukushima (Itoh, 2018; Lyons *et al.*, 2020), or at smaller scales such as following a pipeline leak (Bulot, Provost & Dutoit, 2014).

Ecological restoration and rewilding are both part of a human management continuum, from maximum control (e.g. polluted soil removal, re-introductions) through medium and light actions (e.g. sowing, opening of self-regenerated forest), to no human intervention (mostly found in natural regeneration - sometimes referred to as 'passive' restoration - or passive rewilding projects). Ecological restoration has been considered in this way for many years (Atkinson, 2001; Atkinson & Bonser, 2020; Hobbs & Norton, 1996; Chapman, 2006; Prach & Hobbs, 2008; Holl & Aide, 2011; Chazdon *et al.*, 2021).

Scientists have reflected on the dichotomy between natural regeneration and assisted restoration (sometimes referred to as 'active' restoration). They have highlighted the main difference between them (the time and extent of human interventions), and argued for an intervention continuum concept (Chazdon *et al.*, 2021). When and where to restore actively is a complex question, with answers depending on ecosystem resilience, land-use history, landscape context, desired endpoint and allocated resources (Prach & Hobbs, 2008; Holl & Aide, 2011). The monetary cost of ecosystem recovery increases in general with more intensive human actions and is often a determining factor for choosing the approach (Prach & Hobbs, 2008). Rewilding is also seen as a continuum of scale, connectivity and human management (Hansen, 2010; Svenning *et al.*, 2019; Van Meerbeek *et al.*, 2019; Anderson *et al.*, 2019; Carver *et al.*, 2021), coupled with a wilderness continuum (Gordon *et al.*, 2021*b*). This vision permits reconciliation of rewilding and human influences, which are often opposed (Van Meerbeek *et al.*, 2019), even if human influence is limited to the introduction of ecological engineers and avoidance of intensive human management. As for ecological restoration, the degree of human intervention in rewilding is project dependent. For example, the degree of human intervention initially was substantial for the re-introduction of European bison *Bison bison* Linnaeus into the South Carpathians, but this was followed only by light interventions including monitoring and field surveys, increasing public awareness to help avoid human–wildlife conflict and possible financial compensation (Vlasakker, 2014). Another example involved no human intervention for 33 years after farmland abandonment in the UK, with natural shrub recolonisation (Broughton *et al.*, 2022). The degree of wilderness attempted or attained is also project dependent and strongly depends on the defined or implied goals. The costs and benefits of rewilding projects are difficult to estimate because of the unpredictability of possible difficulties and conflicts, as well as because of their often open-ended goal (Pettorelli *et al.*, 2018). Ecological restoration is well represented in policy (e.g. UN Decade, Bonn Challenge, EU Strategy for Biodiversity) which transfers to its application by stakeholders. On the contrary, rewilding is barely represented in current policy (Pettorelli *et al.*, 2018), likely because of the unpredictable outcomes of rewilding due to its open-ended vision, the lack of practical measurements and the lack of a clear definition of what is considered 'wild' (Rubenstein *et al.*, 2006; Lorimer *et al.*, 2015; Rubenstein & Rubenstein, 2016; Svenning *et al.*, 2016; Schulte to Bühne, Pettorelli & Hoffmann, 2021), which does not fit with a policy focus on protecting and restoring historical states (Pettorelli *et al.*, 2018). Moreover, rewilding is a more recent paradigm and any scientific/management concept will take time to percolate into society, and even more so to affect policy. This may explain why rewilding projects have been mainly implemented by non-governmental organisations (NGOs) and the private sector. However, interest in rewilding has increased and a task force was launched, and followed by the creation of a Thematic Group by the IUCN (at international and national level), to develop a conceptual and methodological framework (IUCN CEM Rewilding Thematic Group; IUCN, 2022).

IV. OUTLOOK

(1) Trends and wider goals

(*a*) *A wider goal for ecological restoration*

Ecological restoration is constantly evolving and scientists are suggesting new paradigms and new perspectives. Some argue for conservation-oriented restoration, including assisted migration (IUCN/SSC, 2013) such as the use of threatened plant species not only where they grow or grew in the recent past but also in suitable new sites (i.e. in a potential distribution range) (Volis, 2016, 2019). Novel ecosystems and unpredictable end-points are other topics of discussion (Pape, 2020). Some have long been calling for a more future-oriented restoration (Choi, 2004, 2007), arguing that open-ended visions of projects and acceptance of novel ecosystems will offer numerous benefits, particularly in the context of climate change (Teixeira & Fernandes, 2020). However, new paradigms such as conservation-oriented restoration and future-oriented restoration do not mean that ecological restoration in its primary form is no longer relevant. These paradigms can be considered as new tools to improve restoration and to adapt to the needs of individual projects (Perring *et al.*, 2013; Hobbs, Higgs & Hall, 2017).

Growing interest in the recovery and management of ecosystem functions in ecological restoration and the need for research (Kollmann *et al.*, 2016), has led to a functional trait-based approach and an argument to link this approach to ecosystem services (Bullock *et al.*, 2011; Carlucci *et al.*, 2020). The functional traits approach differs from the taxonomic approach by focusing not on the composition of species but on the functions they support in an ecosystem (De Bello *et al.*, 2021).

The recovery of trophic structure is another developing focus in ecological restoration (Fraser *et al.*, 2015), and some have underlined the surprising lack of interest on trophic-web recovery in ecological restoration (Miller & Hobbs, 2019). Restoration is often focused on the recovery of producers and indirectly of the trophic web, but the monitoring of restoration projects rarely considers how far trophic interaction recovery has gone or how to enhance interactions through ecological restoration (Cross, Bateman & Cross, 2020; Loch, Walters & Cook, 2020; Ladouceur *et al.*, 2022). Trophic interactions underpin ecosystem functions and services such as pollination, herbivory, and seed dispersal (Ladouceur *et al.*, 2022). As research has underlined (Byers *et al.*, 2006; Kollmann *et al.*, 2016), some ecological functions are not dependent on complex communities but on a few keystone species. Ecological restoration projects have an increasing interest in ecosystem engineers, studying their effects (Rohrer *et al.*, 2020; Maisey *et al.*, 2021) and their role in habitat restoration (De Almeida *et al.*, 2020; Buisson *et al.*, 2021). Meta-analyses have demonstrated that restorative actions can enhance biodiversity and ecosystem services, but that these metrics often differ significantly from those in reference ecosystems (Rey Benayas *et al.*, 2009; Moreno-Mateos *et al.*, 2012; Meli *et al.*, 2014; Barral *et al.*, 2015; Crouzeilles *et al.*, 2017; Marchand *et al.*, 2021; O'Brien, Dehling & Tylianakis, 2022). To counteract this, it has been suggested that ecological complexity – structural heterogeneity, trophic interactions and functional diversity, which can be measured at multiple scales – should be included as goals for ecological restoration projects (Bullock *et al.*, 2022).

These trends could make ecological restoration and rewilding more similar in their goals, especially with the growing interest of the ecological restoration field towards ecosystem functions, trophic chains and the use of ecosystem engineers, which are major parts of the rewilding paradigm (Fig. 1).

(*b*) *A wider role for rewilding*

Even if abandoned agricultural lands in Europe are returning towards semi-natural or being transformed to urbanised landscapes (Fayet *et al.*, 2022), few places can support rewilding in its strict sense (e.g. no management across huge areas) because of limitations, such as social acceptability linked to ethical debates (Thulin & Röcklinsberg, 2020), the need for large areas to support megafauna and to permit connectivity (Bluhm *et al.*, 2023), and historical legacies of previous non-sustainable use, such as pollution. Moreover, the extinction of top predators, large herbivores and ecosystem engineers around the world leads to difficulties in regaining ecological functions even with ecological replacements. These arguments have driven some to reconsider the place of hardy domestic breeds in rewilding projects (Bluhm *et al.*, 2023). Domestic animals may be useful when formal rewilding is not possible because of socio-economic barriers (e.g. need for production, ease of management, and avoidance of conflict) (Gordon *et al.*, 2021*b*) or due to the absence of wild keystone species. It is argued that rewilding *lite* (with the use of livestock) and *max* (with wild animals) offer complementarity in space and time (Gordon *et al.*, 2021*b*).

More recently, there has been discussion about 'megatrees' and the *laissez-faire* approach based on vegetation succession, although historically rewilding tended to focus more on animals, particularly on megafauna. Scientists also are expanding the goals of rewilding, by considering de-extinction for plants (Albani Rocchetti *et al.*, 2021), rewilding with cultivated seagrass meadows (van Katwijk *et al.*, 2021), and rewilding using wild crops and plants to enhance and preserve biodiversity for agricultural goals (Vogt, 2021).

Rewilding is now also being considered in urban places to increase the resilience of cities in face of climate change and to enhance quality of life (Lehmann, 2021). Some argue for the reintroduction of wild animals in large urban parks (e.g. California quail *Callipepla californica* Shaw), with the argument that parks could support such animals and could be connected by wildlife corridors or assisted colonisation could be used (Iknayan *et al.*, 2021).

A wider role of rewilding with greater use of domestic animals instead of wild ones (extinct or not), and also involving plants – increasing the focus on primary producers – and targeting places other than large natural areas, could be other shared goals (Fig. 1).

(*c*) *Invertebrates and microorganisms as an issue for the two paradigms*

Contos *et al.* (2021) recently advocated the consideration and use of invertebrates and microbes in both restoration ecology and rewilding, reminding us of the importance of invertebrates and micro-organisms for natural processes and that still relatively few restoration projects include both plants and animals (McAlpine *et al.*, 2016). For example, soil functions such as decomposition and nutrient cycling, and structural formation of the soil, are considerably influenced by invertebrates and microbial communities, and are

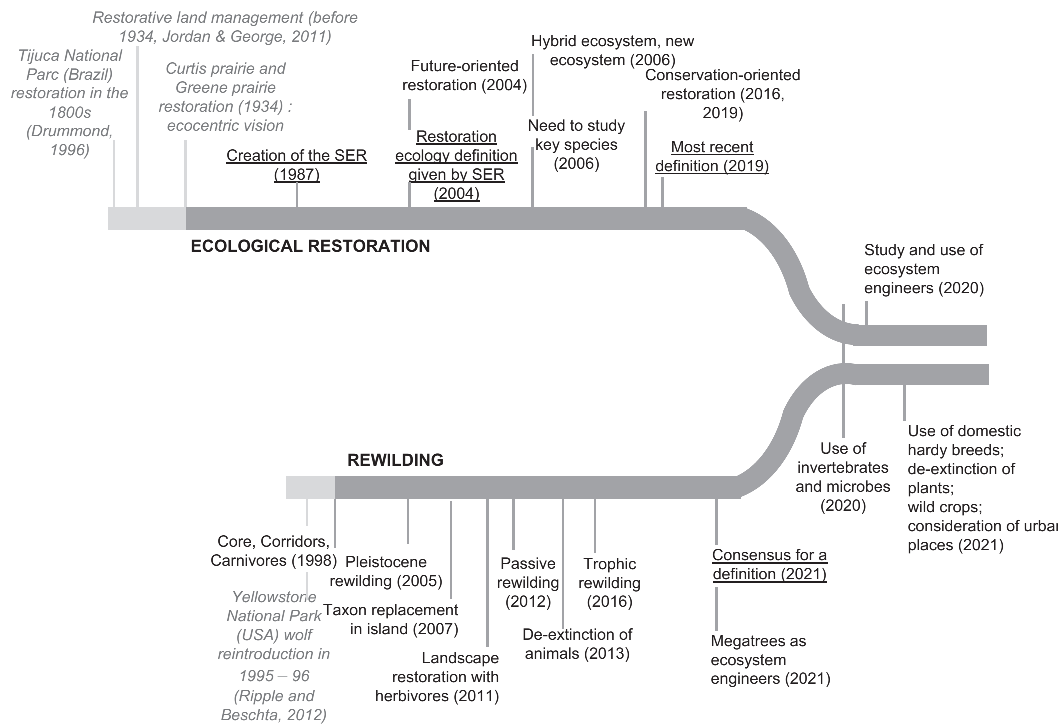

Fig. 1. History resume and trends of ecological restoration and rewilding to 2022. Text written in italic provides early examples of restoration and rewilding projects, although they may not have used these terms. Underlined text indicates consensus definitions and creation of the Society of Ecological Restoration (SER). All other text indicates concepts and proposals for the two disciplines.

particularly important to reinstate to accomplish ecological restoration (Snyder & Hendrix, 2008; Harris, 2009). These aspects have been examined and discussed for soil translocations and inoculations in the framework of ecological restoration (Kardol & Wardle, 2010; Bulot *et al*., 2017; van der Bij *et al*., 2018). Moreover, Contos *et al*. (2021) argue for developing the use of invertebrates in ecological restoration and rewilding projects, because they can be keystone species and can be easily manipulated, and the authors provide a framework for this. Recently, results of active rewilding by transplanting leaf litter along with its invertebrate community, has been shown to improve morphospecies richness rapidly (Contos, Murphy & Gibb, 2022).

(2) Directions for reconciling restoration and rewilding

(*a*) *Complementary approaches*

Ecological restoration and rewilding are often placed in opposition (Nogués-Bravo *et al*., 2016; Prior & Ward, 2016; Cloyd, 2016; Hayward *et al*., 2019*c*,*b*; Derham, 2019; Klop-Toker *et al*., 2020). Expanding the roles of the two strategies (see Section IV) could lead to possible overlaps. However, they provide opportunities for complementarity, notably because they (*i*) have distinct goals using different approaches (e.g. top-down/bottom-up, assisted dispersal, use of ecosystem engineers, etc.) and (*ii*) because their individual limitations could be overcome by combining them (e.g. ethical and practical issues in rewilding could be ameliorated after ecological restoration). For example, it would be possible to free a river from anthropogenic channels, and restore the banks and plant communities to prevent the encroachment of invasive species. Then in a second step, a *laissez-faire* approach could be implemented to increase the stochasticity of natural events and allow the passive return of wild animals, such as herbivores to assist the dissemination of plants. Alternatively, if wild animals important for ecological functions do not colonise naturally, then active reintroduction could be used. An open-ended vision might be accepted if the abiotic composition is similar to natural places – such as removal of human-built river channels – and if the risk of invasive species is decreased by an ecological restoration project. According to Genes & Dirzo (2022) habitat restoration and trophic rewilding are complementary because they focus on the two partners of the plant–animal interaction. Moreover, they are steered by some common points as discussed above (e.g. human management continuum, ecological succession, invertebrates and microorganisms needing further research). This complementarity of approaches can be used in space and time and its synergy could benefit nature recovery.

(*b*) *Complementarity in space*

Ecological restoration and rewilding can be complementary in space. Depending on the goal and the state of degradation, practitioners and stakeholders can choose one approach or

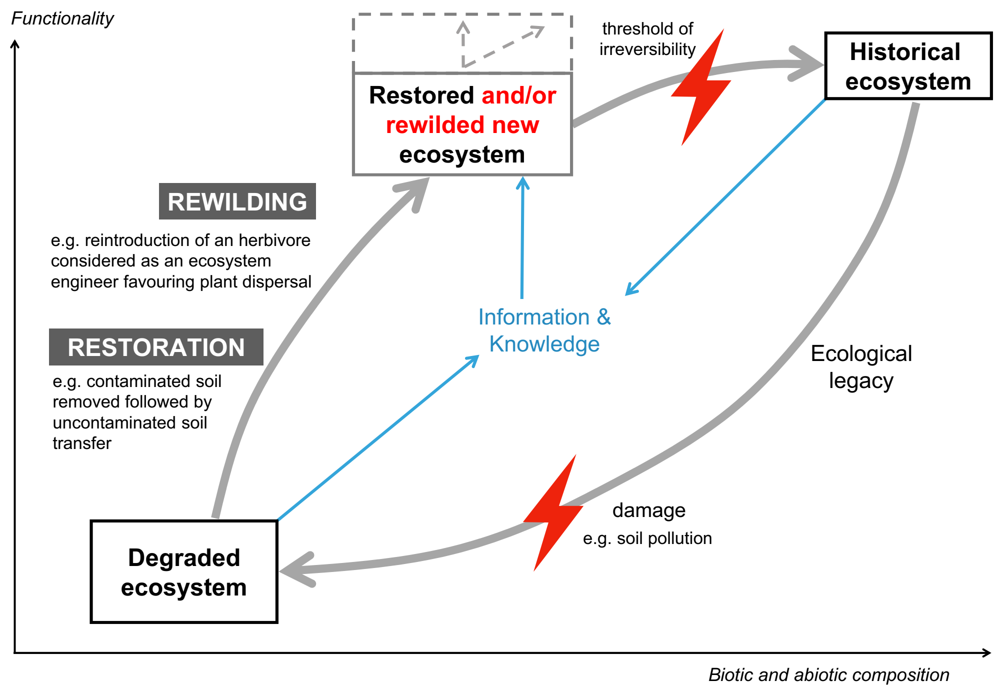

Fig. 2. Hypothetical pathway of a historical ecosystem, which has been degraded, to recovery using ecological restoration followed by rewilding. We emphasise the importance of the ecological legacies used as information and knowledge (represented by blue arrows) to approach the problem and the different alternatives for the restored/rewilded ecosystem which can be considered more or less similar to the historical ecosystem in terms of biotic and abiotic composition (near-historical, hybrid or novel ecosystem *sensu* Hobbs *et al.*, 2009). It is also important to consider the threshold of irreversibility between the restored ecosystem and the historical one. The threshold here assumes that it is impossible to return exactly to the historical ecosystem. The dotted rectangle with the arrow represents the possibility for this new ecosystem to one day be as functional as, although different from, the original ecosystem.

the other, but there is also the possibility of combining the two. There are so many degraded ecosystems in the world that all approaches provide possible solutions. The constraints and aims of a project will influence the choice of approach. It will certainly not be possible to reintroduce top-predators or large wild herbivores everywhere, given the ethical issues (Thulin & Röcklinsberg, 2020) regarding the reintroduction of wild animals and their welfare (e.g. in Oostvaadersplassen; Vera, 2009) or the management needed to avoid human–wildlife conflicts (e.g. grey wolf in France; Espuno *et al.*, 2004). Moreover, when land is polluted, restoring the habitat is a prerequisite to reintroductions of plants and animals. In other cases, pollution may be so intense that letting nature recover by itself is the only solution. The establishment of the Chernobyl exclusion zone after the explosion of a nuclear reactor in 1986 has led to space for nature, and the restoration of threatened species, such as the white-tailed eagle (*Haliaeetus albicilla*; Linnaeus, 1758) and the greater spotted eagle (*Aquila clanga*; Pallas, 1811), and species interactions, such as carrion availability from wolf predation for raptors or top-down control by mesopredators (Dombrovski, Zhurauliou & Ashton-Butt, 2022). It could also be interesting to develop this aspect of spatial complementarity at a landscape scale. For example, rewilded places could be connected by restored sites that cannot support the presence of megafauna but can be used as ecological corridors for other components of biodiversity, such as plants or birds. One possibility (Gordon *et al.*, 2021*b*) is to create a rewilded core zone with an encircling restored zone, which could create an 'acceptance zone', that could become naturally recolonised and eventually rewilded (see Section IV.2.*c* below).

(*c*) *Complementarity in time*

Small-scale restoration (e.g. active restoration of forest ecosystem islets on agricultural land) can drive *laissez-faire* over a larger area (Rey Benayas & Bullock, 2015). Another example considers a heavily disturbed site, such as a reclaimed mine with high level of soil pollutants (Fig. 2). Heavily disturbed sites need more intervention and management (Prach *et al.*, 2020), at least initially. After the removal of polluted soil, here considered as high-intensity human management, it is possible to plant adapted vegetation and to reintroduce ecosystem engineers. Using existing examples of ecological restoration projects, such as steppe restoration after the removal of an ancient orchard (Jaunatre, Buisson & Dutoit, 2012) or after a pipeline leak (Bulot *et al.*, 2014), we can advance a further step within the rewilding paradigm by adding wild herbivores. The restored ecosystem could be either close to the historical ecosystem, a hybrid one, or a novel ecosystem, depending on the local and external factors that drive changes over time. The value of the result could be measured in terms of functionality.

The type of ecosystem requiring restoration is of major importance because it will allow us to understand the biotic–abiotic processes upon which the ecological function is based (Byers *et al.*, 2006) and which processes are absent. Flowcharts can be helpful to decide on potential solutions (Van Meerbeek *et al.*, 2019; Pedersen *et al.*, 2020; Schulte to Bühne *et al.*, 2021) and frameworks have been developed to assess where and when to rewild (du Toit & Pettorelli, 2019; Thierry & Rogers, 2020), and where and when to use ecological restoration (Brancalion *et al.*, 2016).

V. CONCLUSIONS

(1) The brief history of the origin of the two approaches presented herein shows that each has its own roots and has emerged from defined problems and intentions (e.g. bottom-up or top-down regulation). The implementation of each paradigm has illustrated their limitations and allowed the development of definitions. This synthesis has demonstrated that ecological restoration and rewilding are the bases of two different approaches in conservation, but with the same ultimate scope – the recovery of damaged ecosystems – but the ways to get there and the visions of what recovery looks like are different.

(2) So far, rewilding has been adopted less widely, but the urgency of the need to protect and recover ecosystems has resulted in recent enthusiasm leading to discussions about the differences between ecological restoration and rewilding. As both disciplines are expanding their goals, one cannot yet state whether there is a paradigm shift with ecological restoration moving towards rewilding or *vice versa*, or if they are simply converging.

(3) We underline some similarities (e.g. promoting the engagement of stakeholders, being informed by various types of knowledge, supporting ecosystem recovery processes), but also important differences in aims between the two approaches (e.g. taxonomic *versus* functional approaches, a defined target ecosystem *versus* no endpoint, project scale and acceptance of taxonomic replacements for rewilding), which inform potential complementarities that can be applied in space and time. These approaches belong to a continuum of restorative activities, and projects can comprise both ecological restoration and rewilding. We argue for reconciliation between these approaches: one does not necessarily exclude the other, and used together they may be able to improve the recovery of ecosystems. Practitioners and researchers of both approaches should consider the literature regarding both disciplines in order to integrate these knowledge bases.

(4) A current priority is to conserve existing ecosystems which preserve biodiversity and primary ecological functions. Restoration ecology and rewilding reflect the fact that we have failed in many places to conserve functional ecosystems with all their complexity and trophic levels. There are still many questions regarding which areas to target, what baselines to use, which animals and plants to conserve, and which futures we envision. Many ecological restoration projects have limitations. On the other hand, if rewilding projects proliferate, there are still few scientific studies concerning their ecological outcomes; such studies could help to develop and reinforce knowledge, and thus improve future work. In addition, future studies should aim to investigate the design in space and time of the multiple options offered by the complementarity of these two disciplines to benefit biodiversity at all levels.

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